Beyond biofuels, agriculture's dark side vs Solar Fuels (Artificial Photosynthesis)

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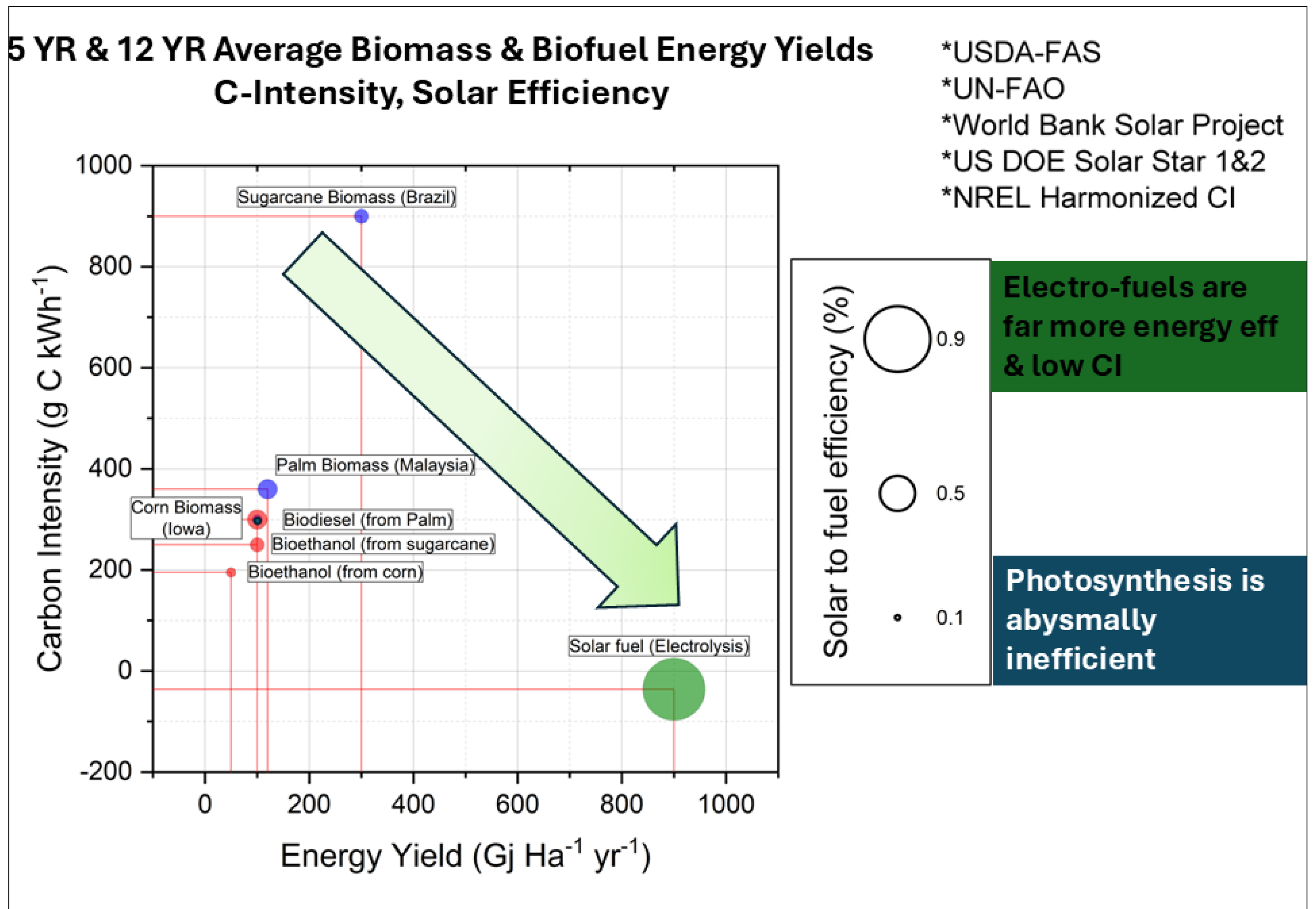
SUMMARY

Energy crops (corn sugarcane, oil palm) are used to produce ethanol and biodiesel. Biofuels require 9-fold more land area and are 9-fold less energy efficient than are electro-fuels made from solar electricity. They are net emitters of CO_2 while electro-fuels are net consumers of CO_2. Here we provide quantitative comparisons of their solar efficiency, carbon emissions and land use relative to solar electricity and solar fuels, aka electro-fuels (**Fig 1 & Table**).

RESULTS

Biofuels are produced mainly from dedicated energy crops and commercial forestry wastes. Contrary to common misrepresentation, they are not mainly sourced from agricultural wastes associated with food and feed crops. Another common misrepresentation is they are produced from super-efficient energy crops. None exist.

Here we summarize field data for solar energy conversion to biomass then to biofuels (**Table & Fig 1)** from long running, globally distributed, independently validated, commercial energy crop farming of corn, sugarcane and oil palm (**column B1**). Together with independent solar insolation data for each farming site **(column A2),** the solar-to-biomass efficiency is 0.26% to 0.5% even for the most efficient energy crops (**column D1)**. Subsequent conversion to a biofuel (ethanol or biodiesel) produces an additional 2-fold loss in energy capture for the overall STBF conversion efficiency of 0.13 to 0.26% (**column E1)**.



Data taken from Table 1; Graph is unpublished

<u>This comparison shows that biomass energy crops are 16 to 32-fold less efficient **(Columns D2 versus D1)** in capturing solar energy per unit area and storing it as usable chemical energy (dry biomass) compared to existing solar cells that were installed 9 years ago. Decades of research have not appreciably improved the intrinsic solar-to-chemical energy conversion efficiency of natural photosynthesis (<0.5%), while solar PV efficiencies have continued to increase (~22% today)(*6*).</u> <u>**The corresponding overall efficiency for conversion of sunlight to solar fuel is 3 to 5-fold greater than any biofuel (column E2).**</u>

ACKNOWLEDGMENTS

- Funded by the Department of Energy, Basic Energy Sciences, DE-FG02-10ER16195. Critical input from Marie-Claire ten Veldhuis & Shubham Gupta.

	Energy Input A1	Biomass Output B1	Biofuel Output C2	Energy output / Solar input D1	E1	Carbon Intensity F1
	Solar [c] insolation GJ/ha/y	Dry biomass (mtons) GJ/ha/y	Biofuel[b] (mtons) GJ /ha/y	% Conv. Eff. Solar to biomass =B1/A1	% Conv. Eff. Solar to biofuel = C1/A1	gram CO_2 kW^{-1}
Sugarcane (Brazil, Sao Paulo)	66852	(17) 333	(4.8) 128	0.50	0.19	>corn CI
Corn (US, Iowa)	58320	(8.0) 149	(2.8) 74	0.26	0.13	+ 195
Palmoil (Malaysia, Sarawak)	37332	(6.4) 125	(2.6) 97	0.33	0.26	>corn CI
	A2 Solar input	B2 PV-Electrical output	C2 Synthetic fuel output	D2 = B2/A2 % Conv. Eff.	E2 = C2/A2 % Conv. Eff	F2 Carbon Intensity
	Solar insolation GJ/ha/y	PV Electricity GJ/ha/y	Syn fuel GJ/ha/y	Solar to PV	Solar to Synfuel	gram CO_2 kW^{-1}
PV Electric Solar Star Rosamond CA, USA	106956	4625		4.3		+ 10
PV + CO_2 Electrolysis			879[a]		0.82	- 36

a) Based on 19% conversion efficiency of electrical energy to synthetic fuels (*9*)

b) Using the reported biodiesel production yield for Malaysian palm oil (2.6 ± 0.2 tons/ha-y) (*3, 4*)

c) The direct solar insolation at each site(*8*)

REFERENCES

1. Department of Energy, *2016 BILLION-TON REPORT : Advancing Domestic Resources for a Thriving Bioeconomy* (2016) https://bioenergykdf.net/2016-billion-ton-report.
2. M. C. Rulli, D. Bellomi, A. Cazzoli, G. De Carolis, P. D'Odorico, The water-land-food nexus of first-generation biofuels. *Scientific Reports* **6**, 22521 (2016).
3. Hugo Valin, e. al. (European Commission: ECOFYS Netherlands B.V, 2015), vol. Ref. Ares(2015)4173087 - 08/10/2015.
4. H. Ritchie, M. Roser, in *OurWorldInData.org*. (https://ourworldindata.org/palm-oil, 2021).
5. T. Capehart, S. Proper, in *https://www.usda.gov/media/blog/2019/07/29/corn-americas-largest-crop-2019*. (USDA-Economic Research Service, in Research and Science, 2021).
6. J. Svarc, in *Most efficient solar panels 2022,* M. Newkirk, Ed. (2021).
7. K. Lewis *et al.*, An assessment of oil palm plantation aboveground biomass stocks on tropical peat. *Scientific Reports* **10**, 2230 (2020).
8. G. anonymous, in *Solargis s.r.o*. (World Bank Group, 2022) https://globalsolaratlas.info/map?c=2.502385,112.954728,11&s=2.502385,112.954728&m=site.
9. J. E. Huang *et al.*, CO₂ electrolysis to multicarbon products in strong acid. *Science* **372**, 1074-1078 (2021).
10. *Sugar Annual: Agricultural Trade Office_Sao Paulo Brazil* (BR2021-0015, 2021 https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Sugar%20Annual_Sao%20Paulo%20ATO_Brazil_04-15-2021.pdf).
11. *National Agricultural Statistics Service (NASS)* (2022 access January https://www.nass.usda.gov/Charts_and_Maps/Field_Crops/cornprod.php).
12. X.-G. Zhu, S. Long, D. Ort, What is the Maximum Efficiency With Which Photosynthesis can Convert Solar Energy into Biomass? *Current opinion in biotechnology* **19**, 153-159 (2008).
13. T. W. Patzek, A Statistical Analysis of the Theoretical Yield of Ethanol from Corn Starch. *Natural Resources Research* **15**, 205-212 (2006).
14. EIA anonymous, in *Electricity Data Browser*. (Energy Informaton Agency, https://www.eia.gov/electricity/data/browser/#/plant/58388/?pin=ELEC.PLANT.GEN.58388-SUN-ALL.M&linechart=ELEC.PLANT.GEN.58388-SUN-ALL.M).
15. Y. Xiao *et al.*, An artificial photosynthetic system with CO2-reducing solar-to-fuel efficiency exceeding 20%. *Journal of Materials Chemistry A* **8**, 18310-18317 (2020).
16. NREL anonymous, in *NREL Energy Analysis*. (NREL, https://www.nrel.gov/analysis/life-cycle-assessment.html, 2022 accessed January).

CARBON INTENSITY

Electricity consumption is the main cost and source of greenhouse gas (GHG) emissions for AP fuel processes. For each C atom in the fuel molecule, one CO_2 molecule is consumed. Therefore, AP systems have the potential for net *carbon negative emissions* when powered by renewable electricity. To quantify this, we consider the **National Renewable Energy Laboratory (NREL)** study of **46 independent life cycle analyses (so-called harmonized LCA)** for PV power production. NREL determined the proportions of all GHG emissions from each stage of PV power production (fabrication/installation, operation and decommissioning) and compared it to a baseline of coal-based power (*16*). For this generic PV power plant, the sum of all GHG emissions is 25-fold lower (~40 g CO2eq/kWh) compared to coal power production (~ 1000 g CO2eq/kWh). The NREL study found that the portion of GHG emissions arising from PV operation is a minor fraction ~23.5% (9.4 g CO2eq/kWH produced) **(column F2)**, versus >98% (>980 g CO2eq/kWH) for operation of coal power plants. In the AP process, this operational CO_2 emission from PV electricity production is offset by the amount of net CO_2 consumed during operation of the electrolyzer. Using the aforementioned AP process (producing ethylene and propanol from pure CO_2 at 19% efficiency), the consumption of 1 kWh of electrical energy will produce 0.19 kWh equivalents of C2 + C3 products, which is equal to the consumption of 1.0-1.1 eq CO_2 (~ 46 gCO_2). <u>The combined STAP process has a net *consumption* of -36g CO_2 eq per kWh of PV electrical energy **(column F2**), or four times greater CO_2 consumption than emission potential.</u> By contrast, the net carbon emission of advanced corn ethanol production based on the most widely accepted LCA model including land use change is 195 g CO_2 kWh^{-1}(*18*) (*19*) **(column F1)**. <u>For every kW equivalent of corn ethanol production that is replaced by AP generated solar fuel there would be a net reduction in carbon emission of 231 g CO_2 kWh^{-1}.</u>

Solar to Electricity to Solar Fuels

Next, these numbers are compared to the reported solar energy input **(columnA2)** and the electrical energy output from the longest-running large-scale solar photovoltaic (PV) farms in California, USA (*14*). The continuously monitored production of solar electricity was taken from the Solar Star 1&2 commercial PV farm over a 5 year period (**Column B2**) to obtain the energy conversion efficiency of 4.3% (**column D2 = B2/A2**).

Solar to Fuels by Electrolysis. Renewable solar and wind electricity can serve a wide range of energy uses but are use-it-or lose-it energy sources, and thus not a direct replacement for biofuels required for heavy vehicle traffic. This needs a further conversion step, for which renewable solutions are now becoming available. Recent advances have shown that electrolysis of CO_2 and water can produce small carbon-containing molecules (C1, C2, C3 and C4) on selective electrodes (electrocatalysts) (*9*). These chemicals can be used directly as fuels or as precursors to upgraded fuels after separation and purification. For example, on copper electrodes, 50% of the current produces C2+C3 products, while the other half makes H_2. <u>The overall electrical energy conversion efficiency for an electrochemical process is</u> the product of the current conversion efficiency (here 50%) times the cell voltage efficiency. For the illustrated example at the operating voltage of 4.2 V the overall electrical to synthetic fuel energy conversion efficiency (ETSF) to C2+C3 products is 19% (**Table**)[1]. This Artificial Photosynthetic (AP) process, if powered by the aforementioned Solar Star 1 & 2 electrical farm would have an annual solar-to-AP-fuel efficiency (STAP) of 0.82% (**Table**) > 10X better than biofuels.